

New Observing Techniques

D.L. Welch

*Department of Physics & Astronomy, McMaster University
1280 Main St W, Hamilton, ON L8S 4M1 Canada*

Abstract. The influence of new techniques on the discovery and characterization of pulsating variables has been enormous. In this paper, I will review the methods and results of a number of research programmes which have dramatically altered our ability to study variable stars and will likely bear fruit for many years into the future. Specifically, I will touch on results from the MACHO and EROS Projects, the HIPPARCOS mission, "flux difference" photometry and a handful of new algorithmic advances which I consider to be important.

1. Introduction

The pace at which new and better instrumentation has become available to astronomers has accelerated in the last decade. Furthermore, improvements in algorithms and computers have allowed the astronomer to embark on "computationally expensive" projects which were unthinkable only ten years ago. In this review, I select a handful of research programmes which have had a large impact on the study of variable stars and review several relatively new techniques which I feel will lead to improvements in analysis in the near-future. I have made no attempt to be complete as completeness may be next to godliness, but it is also next to impossible in the time and space permitted. I apologize for my (many) errors of omission.

2. Massive Photometry

2.1. MACHO

<http://www.macho.mcmaster.ca/>

The MACHO Project is the first of the microlensing surveys I will discuss. A joint collaboration of the US Department of Energy (Lawrence Livermore National Laboratory), National Science Foundation (Center for Particle Astrophysics), and the Australian Commonwealth Science and Industrial Research Organization (Australian National University/Mount Stromlo Observatory), the Project's primary goal is to determine the characteristics of non-luminous or under-luminous matter in the Milky Way by detecting the amplification of starlight as a result of gravitational microlensing.

The state of the MACHO Project during 1996, including a description of equipment and computational procedures, is given by Cook *et al.* 1997. Briefly, the dedicated 50-inch telescope at Mount Stromlo Observatory, uses a custom-built camera containing two arrays of four 2048×2048 CCD detectors to obtain simultaneous red and blue images of field in the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and the bulge of the Milky Way galaxy. Since 1992, over 50,000 image pairs have been obtained in the course of approximately 1800 nights. The photometry is processed by a multi-CPU system which ensures that data obtained on one night is completely processed before the next night. At present, some of our fields have as many as 1500 different observation epochs.

The suitability of such a database for variable star work is obvious and there have been many variable star papers published, primarily discussing LMC results. I will briefly describe each of the major results:

- *Double-mode RR Lyrae* — Alcock *et al.* (1997a) reported the discovery of 75 RRd stars in the LMC, all new. Pulsation parallaxes for the ensemble suggest an LMC distance modulus of 18.48 ± 0.19 mag for the LMC.
- *Double-mode Cepheids* — Alcock *et al.* (1995, 1998a, 1998b), Welch *et al.* (1997), and Rorabeck (1997) have reported the detection of large numbers of double-mode Cepheids in the LMC and SMC. These detections reveal the presence of first and second overtone beating in addition to stars beating in the fundamental and first overtone stars. Furthermore, the period ratios and location of stars in the instability strip are quite clearly correlated with metallicity in the manner described by Morgan & Welch (1997). Singly-periodic second overtone Cepheids have also been identified in the LMC.
- *Classical Cepheids* — Welch *et al.* (1997) has reported the progress on singly-periodic classical Cepheid variables. The complete sample of 1477 LMC Cepheids has been analysed and mean lightcurve properties have been derived. Detectable amplitude changes are seen in about 1% of the sample.
- *R CrB Variables* — Alcock *et al.* (1996) reported the discovery of three new spectroscopically-confirmed LMC R CrB stars. These stars reveal that the mean absolute magnitude for R CrB stars is likely about one magnitude fainter than traditionally assumed. At present, about one dozen R CrB stars have been discovered by the MACHO Project.
- *W Virginis/RV Tauri Stars* — Alcock *et al.* (1997b) have presented photometry and analysis for LMC W Virginis and RV Tauri variables. Such stars have been relatively neglected because their longish-periods and slightly erratic behavior makes short time-series difficult to interpret. The period-luminosity (P-L) relation for these stars are consistent with a common origin with the RV Tauri stars forming the long-period extension. Furthermore, irregularities in the lightcurve appear first in the 15-20 day period range and get progressively larger with increasing luminosity (and period).

- *HV 5756 - An Eclipsing Type II Cepheid* — Welch *et al.* (1996) report the discovery of the first type II Cepheid in an eclipsing binary system. The Cepheid, HV 5756, was known from Harvard College Observatory studies. However, the MACHO Project data reveals that this 17.5 day pulsator also undergoes eclipses at 419 day intervals, the most recent primary eclipse being 1997 Sep 11. The companion is a hotter star which apparently has a luminosity significantly above that of the horizontal branch in the LMC. This system provides the first opportunity to obtain a dynamical mass for a type II Cepheid.
- *Long-period Variables* Cook *et al.* (1997) revealed the presence of at least three sequences of long-period variables in a plot of the surface brightness-corrected magnitude versus log P plot of singly-periodic variables in the first-year LMC variable star analysis. These appear to represent the fundamental, first-, and second-overtone sequences for LPVs. The photometric amplitude of the lightcurves is strongly correlated with the sequence.

2.2. EROS

<http://www.lal.in2p3.fr/EROS/presa.html>

The French microlensing survey, EROS, has produced a number of significant results in the area of pulsating variables. Results reported in the literature to date are from EROS 1 which employed a 0.6m telescope and produced very extensive time-series (2-3× larger by epoch number) than MACHO, for single fields in each of the LMC and SMC. At present an improved, larger-area survey called EROS 2 is underway. The larger field and greater sensitivity of the second project promise many new results for the study of variable stars in the LMC and SMC. Major results related to pulsating variable stars are:

- *Cepheid P-L-C-[Fe/H]* — Sasselov *et al.* (1997) have used two-color photometry for 481 LMC and SMC Cepheids as well as sensible reddening law constraints to derive a metallicity dependence for Cepheid luminosities. They apply this to recent Hubble Space Telescope Cepheid survey results and reinterpret the derived Hubble constant.
- *SMC Beat Cepheids* — Beaulieu *et al.* (1997) reported the discovery of the first 11 beat Cepheids in the SMC. Four were fundamental/ first-overtone pulsators and the remainder were first/second-overtone variables. The fundamental/first-overtone beat Cepheids have period ratios higher than their LMC counterparts due to the lower metallicity of the SMC population, as expected.
- *LMC Classical Cepheids* — Beaulieu *et al.* (1995) presented the analysis of 97 Cepheid stars in the bar of the LMC from EROS 1 data. They found one double-mode Cepheid and reported the clear separation of first-overtone and fundamental mode sequences in the P-L relation. Furthermore, they confirmed the existence of the long-period overtone variables, sometimes called "long-period s-Cepheids".

2.3. OGLE

<http://www.astrouw.edu.pl/~ftp/ogle/index.html>

The third large microlensing project, OGLE, concentrated on studying the Milky Way bulge in its first incarnation. Largely confined to observations in a single bandpass, and with the variable extinction present along the line-of-sight, its pulsating star results towards the bulge have been less useful than other surveys. However, it has since studied variables in globular clusters and dwarf galaxies and these works will likely be of great value in understanding the population characteristics of low-mass pulsating stars.

The successor of the original project is OGLE 2, for which a new 1.3m telescope was built at Las Campanas, Chile.

3. HIPPARCOS

The HIPPARCOS satellite mission and its first results indicate that variable star populations studies have entered a new era. The most recent results can be obtained from the European Space Agency's HIPPARCOS Web page:

<http://astro.estec.esa.nl/Hipparcos/hipparcos.html>

Specifically, the mission provides astrophysicists with three major databases: 1) multiple-epoch, uniform photometry, 2) high-precision proper motions, and 3) uniform, precise parallaxes. The very first results from the mission concentrated on the Cepheid (Feast & Catchpole, 1997) and RR Lyrae distance indicators - the latter through their luminosity calibration by sub-dwarf parallaxes and the subsequent re-determination of globular cluster distances (Reid, 1997). Cepheids are sufficiently rare in the local volume that the parallax of only one star was significant. The interpretation of the Cepheid result is further compounded by the fact that Polaris (α UMi) is an amplitude-changing star whose pulsation mode can only be decided by consistency arguments.

The long-awaited parallaxes of nearby δ Scuti stars by Hog & Petersen (1997) confirm that the currently held belief that large-amplitude δ Scuti stars are normal stars evolving through the instability strip. Another important result is the first set of parallaxes from HIPPARCOS for 16 Mira (large-amplitude) long-period variables by van Leeuwen *et al.* (1997). This study confirms the presence of both fundamental-mode and first-overtone mode pulsators among these variables, with the first-overtone mode being more common among the stars studied.

4. Algorithms

4.1. Robust Detection

A serious consideration for large surveys is the number of "false positive". Simply put, the fraction of stars which are true variables in the field is roughly 1 in 250. However, the total number of stars in a survey is typically 10^7 . So a rate of false positives of 10^{-4} would be required for the false positive sample to be the

same order of magnitude in size as the actual variable star sample. Clearly, a suppression of false positives of a further factor of at least 100 would be desirable.

A workable and very robust technique for detecting variables in the presence of “photometric blunders” was described by Welch & Stetson (1993). It makes use of the estimated uncertainty of each point and the temporal coherence of the lightcurve to retain true variables while rejecting the vast majority of false positives. Furthermore, straightforward tests for the presence of systematic errors are easily implemented so that confidence regions for true variability with real data are easily established.

4.2. Automated Classification

It has long been desirable to have a method of variable star classification which does not involve human intervention. Despite this longing, until recently, even the variable stars discovered in Hubble Space Telescope surveys were classified by eye. While the relatively small number of stars in such surveys makes this a workable scheme, the number of variables generated by the large microlensing surveys begs for something more automatic.

The first significant paper regarding automated classification of variables in the modern era is that of Stetson (1996). An algorithm is both described and tested in this remarkable paper which reduces unanalysed IC 4182 data from HST and compares it to a ‘classical’ search made with earlier HST data. The automated technique produced essentially identical results for the Cepheids. An improved Lafler-Kinman statistic also is derived which reduces the effective weight of phase gaps. This paper should be required reading for anyone embarking on a large photometry program!

4.3. Time-series Analysis

A number of additional time-series analysis algorithms and tools have become available in the last few years. In my mind, the most significant of these is the “CLEANest” algorithm by Grant Foster, described in both Foster (1995, 1996a, 1996b). This algorithm is *extremely* robust for identifying real frequencies in the presence of very strong aliasing - a problem which pervades astronomical time-series analysis. Starting from the “Date-Compensated Discrete Fourier Transform”, or DCDFT as it is more commonly known, CLEANest is used to build a model of lightcurve behavior which simultaneously incorporates all statistically-significant frequencies and removes the effect of their aliases.

A DOS version of this program with a graphical user interface written by Foster which includes sample data files and documentation is available from the American Association of Variable Star Observers (AAVSO) site at the URL:

<http://www.aavso.org/programs/software.html>.

A Fortran77 version, coded by Andrew Rorabeck while at McMaster University, is available from the author. This version has no graphical interface and makes use of the commonly available “Numerical Recipes” subroutines of Press *et al.* (1986). Requests for electronic versions of the code may be made to welch@physics.mcmaster.ca.

Another algorithm worthy of note is the “Analysis of Variance” or “AoV” method of Schwarzenberg-Czerny (1989) which is computationally far less expensive than CLEANest.

4.4. “Flux Difference” Photometry

Perhaps the most elegant new technique described in recent memory is “flux difference” photometry. This is a procedure which allows variable objects to be identified and studied in relatively high signal-to-noise data which is confusion-limited. Said differently, in situations where several stars may be within the angular bounds of a given pixel and hence any particular one may be indistinguishable in an image, it is still possible to study the nature of a variable object, so long as the zeropoint of the flux for a single star is not required.

The most extensive description of the process of reducing data in this manner is the paper by Tomaney & Crotts (1996). This work, made significantly more difficult than expected by a quickly varying point spread function across the frames used for test purposes, reveals the high significance with which strongly crowded variables may be detected. Immediate applications for the search for microlensing using nearby galaxies are obvious. However, there are numerous variable star populations programmes which might be most profitably attacked with these methods. For instance, the period ratios of double-mode stars may be measured as a function of galactocentric radius in galaxies with metallicity gradients, such as M31. Studies of the time-series of relatively rare stars of intermediate luminosity will also benefit by the larger effective search field that this technique employs.

5. Conclusion

A final word. It is my opinion that the most tasty fruit is yet to be picked from the vine. It would be true to say that most of the published results from the major surveys were the most easily extracted and understood. The very long time-series produced by on-going surveys are ideal for studying more difficult multimode behavior and secular trends in stellar properties. Ultimately, I believe that these will have the most lasting impact on progress in our understanding of pulsating stars. Clearly, much remains to be done and the public availability of the time-series will ensure that the impact of each project will continue to be felt long after the last exposure is taken on a given telescope.

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The slides for the PowerPoint presentation given at the meeting are available at the URL:

<http://wwwmacho.mcmaster.ca/LANL97/>

References

- Alcock, C. *et al.* 1998a, AJ, (submitted)
Alcock, C. *et al.* 1998b, AJ, (submitted)
Alcock, C. *et al.* 1997b, AJ, (submitted)
Alcock, C. *et al.* 1997a, ApJ, 482, 89
Alcock, C. *et al.* 1996, ApJ, 470, 583
Alcock, C. *et al.* 1995, AJ, 109, 1653
Beaulieu, J.-P., *et al.* 1997, A&A, 321, L5
Beaulieu, J.-P., *et al.* 1995, A&A, 303, 137
Cook, K.H. *et al.* 1997, in the Proceedings of the 12th IAP Colloquium "Variable Stars and the Astrophysical Returns of Microlensing Surveys", 17
Feast, M.W., & Catchpole, R.M. 1997, MNRAS, 286, L1
Foster, G. 1996b, AJ, 111, 555
Foster, G. 1996a, AJ, 111, 541
Foster, G. 1995, AJ, 109, 1889
Hog, E., & Peteresen, J.O. 1997, A&A, 323, 827
Morgan, S.M. & Welch, D.L. 1997, AJ, 114, 1183
Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T. 1986, "Numerical Recipes - The Art of Scientific Computing", (Cambridge: Cambridge University Press)
Reid, I.N. 1997, AJ, 114, 161
Rorabeck, A. 1997, M.Sc. Thesis, McMaster University
Sasselov, D.D. 1997, A&A, 324, 471
Schwarzenberg-Czerny, A. 1989, MNRAS, 241, 153
Stetson, P.B. 1996, PASP, 108, 851
Tomaney, A.B., & Crotts, A.P.S. 1996, AJ, 112, 2872
van Leeuwen, F. *et al.* 1997, MNRAS, 287, 955
Welch, D.L. *et al.* 1997b, in the Proceedings of the 12th IAP Colloquium "Variable Stars and the Astrophysical Returns of Microlensing Surveys", 205
Welch, D.L. *et al.* 1996, IAU Circular No. 6434
Welch, D.L., & Stetson, P.B. 1993, AJ, 105, 1813